

True Superconductivity in a 2D "Superconducting-Insulating" System

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We present results on disordered amorphous films which are expected to undergo a field-tuned Superconductor-Insulator Transition. Based on low-field data and I-V characteristics, we find evidence of a low temperature Metal-to-Superconductor transition. This transition is characterized by hysteretic magnetoresistance and discontinuities in the I-V curves. The metallic phase just above the transition is different from the "Fermi Metal" before superconductivity sets in.

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The two-dimensional (2D) Superconductor-Insulator (SI) Transition has attracted widespread attention in recent years [1]. Initially, theory argued for the existence of a magnetic field tuned, continuous phase transition from a superconducting to an insulating state, with a quantum critical point and corresponding quantum critical scaling about a critical field H_{SI} [2-4]. Experiments seemed to confirm this scenario, although there was some concern that the apparent critical exponents resembled those expected from classical percolation [5] and that the critical resistance at the transition was not the quantum of resistance for Cooper pairs, $h/4e^2$ [6-8]. However, recent experiments [9-11] have challenged the general existence of such a transition, demonstrating that the apparent transition is only a crossover to a new metallic state at low temperatures. Similar results have been obtained on quantum Hall liquid-to-insulator transitions and on arrays of Josephson junctions; both are presumed to be in the same universality class as the 2D SI transition [12-14]. The question of whether a true superconducting phase is possible within this new experimental situation was an unresolved issue.

In this paper, we present results on magnetoresistance and current-voltage measurements carried out on 2D films of MoGe below H_{SI} . Observations of a dramatic drop in resistance at a critical magnetic field $H_{SM} \ll H_{SI}$, along with corresponding hysteresis near that field and instabilities in I-V curves, point to the existence of a low-field quantum phase transition, possibly a first order one, to a true superconducting state. The metallic phase above the transition is not a normal Fermi Liquid, at least in any simple sense, because its resistance is orders of magnitudes smaller than the normal state ("Fermi") resistance, it has very large magnetoresistance, and it exhibits non-linear transport unlike a conventional metal. The superconducting state can be characterized by vortices (far separated due to the low field) that are pinned on impurities to provide the true zero resistance.

Samples for which we present data in this paper are 30Å and 40Å $Mo_{43}Ge_{57}$ thin films, sandwiched between insulating layers of amorphous Ge on SiN substrates. The 30Å and 40Å samples have sheet resistances at 4.2K of $R_N \sim 1300 \Omega/\square$ and $R_N \sim 800 \Omega/\square$, respectively; T_C 's of 0.5K and 1K; H_{C2} 's of 1.4T and 1.9T. Previous studies have determined the films to be amorphous and homo-

geneous on all relevant length scales. We patterned the films into 4-probe structures, and measured them in a dilution refrigerator using standard low-frequency lock-in techniques. Data was taken at a measurement frequency of $f_{AC} = 27.5\text{Hz}$ with an applied bias of 1nA (well within the Ohmic regime). Current-voltage characteristics were measured as dV/dI curves, using battery-operated electronics to add a slow DC ramp voltage to a lockin AC output.

Figure 1 shows a magnetoresistance curve for a 40Å sample, for temperatures 50mK and 200mK. The field and temperature dependencies at higher fields were examined previously on similar samples [6,9,10]. The temperature-independent "crossing point" – apparent in both the main figure and in more detail in the inset – is expected from scaling theories [3], and is of similar magnitude and quality as that obtained previously on similar samples. Below the crossing point, the temperature curves spread and enter an "activated" regime, where $R \sim e^{U(H)/T}$ and the derived activation energy, $U(H)$, is consistent with $U(H) = U_0 \ln(H_0/H)$, a form expected in the collective creep regime of vortices [15] (here U_0 is of order of dislocation energy and H_0 is approximately H_{c2}). At lower fields, the different temperature curves collapse onto each other, with the lower temperatures collapsing at higher fields (this occurs at 750 Oe for 100mK, and 500 Oe for 200mK, for example): this collapse marks where the system enters a temperature-independent regime previously associated with quantum tunneling [9]. While it was previously unclear whether this "metallic" region (of finite, temperature-independent resistance) persisted to zero temperature, it is now evident that the system enters a new phase at very low fields. Near 0.1 T, the resistance suddenly drops by more than 3 orders of magnitude, approaching zero resistance to within the limits of our measurement. As seen from Figure 2, this drop is best fit by $R \sim 60(H - 0.085)^\mu$ with $\mu \sim 1$. A kink in the magnetoresistance interrupts the power law and a true zero resistance state seems to occur below ~ 185 Oe (see inset of figure 2). Additional data taken for other films of different R_N showed similar behavior. Previous experiments have determined that resistance saturation of lower R_N films seems to occur at temperatures below our measurement capabilities [9]. However, magnetoresistance curves for these films do show the same qual-

tative behavior as the higher resistance films, with the data shifted to higher fields and lower resistance values.

To better examine the low field superconducting behavior, we took more sensitive resistance measurements for a small field range around zero. Figure 3 shows magnetoresistance measurements at 100mK for field up and down sweeps from -600 to 600 Oe. The data clearly shows an increase from zero to finite resistance around 185 Oe – evidence of a critical field, H_{SM} , for the transition to a true superconducting state. The up and down sweeps are symmetric around zero above ~ 400 Oe, but asymmetric and hysteretic below. The curves are independent of temperature below 100mK, and are not affected by changes in bias current to within 2 orders of magnitude. The value of the critical field corresponds to a vortex separation of $\sim 5\xi_0 - 7\xi_0$, where ξ_0 is the vortex core size.

Further evidence of a low field phase transition to a superconducting state is evinced by the dV/dI curves. Figure 4 shows typical dV/dI curves for a 30 Å film at 20mK and fields of 0.2 and 0.1 Tesla. The 0.2 T curve is at the end of the "flattened" region of the magnetoresistance curve, and has a temperature dependence consistent with quantum tunneling of vortices. The peak, evident at $\sim 1.2\mu\text{A}$ with a value almost four times the normal state resistance, is typical for both vortices in the flux-flow regime (see e.g. [16,17]) and Josephson Junctions. Examination of the high current regime suggests that the system's behavior is more similar to that of Josephson Junctions than to flux flow vortices, since the leveling resistance at high bias current is approximately the normal state resistance (i.e., more than 10 times the calculated flux flow resistance). At low fields and high currents the sample seems to enter a new regime: the structure evident in the 0.1 Tesla curve – peaks in dV/dI , or discontinuities in I-V – manifests sample behavior near H_{SM} . This curve is both reproducible and hysteretic. Discontinuities in I-V characteristics are likely due to vortex jumps and local heatings. This can be caused by local inhomogeneities in the sample, possibly phase separation into regions with different critical currents. This behavior has been seen in other systems, also near quantum phase transitions [11].

The above results clearly point to a new physical situation of the superconducting film at low temperatures and magnetic fields below the upper critical field. For instance, we observed a wide range of magnetic fields for which the system is a metal at $T = 0$. The metallic phase stabilizes at very low temperatures, and is far from being a simple extrapolation of the normal state "Fermi-metal" that we observed just above the bulk transition temperature. This new metal is characterized by very low resistance; as can be seen from Figure 1, at 0.2 T this resistance is more than two orders of magnitude below the normal state resistance. At that field the resistance is temperature independent below $\sim 150mK$ [10]. Furthermore, this unusual metal has very strong magnetoresistance, especially very close to the true superconducting

transition H_{SI} . The transport is different from a conventional metal in that the I-V are non-linear at relatively low currents. The overall shape of the I-V characteristics resembles that of a resistively shunted Josephson-junction. The transition into the superconducting state is also unusual because it is strongly hysteretic. Such behavior is clear evidence for the existence of vortices. The origin of the hysteresis could be due to either a genuine first order transition to the true superconducting state, or else a dynamical consequence of a glassy state in which the relatively low density of vortices are frozen. In the latter case, this would be the first observation of the long sought vortex-glass phase in 2D superconductors [4].

Typical theoretical treatment of the SI system is to map it onto the so-called "dirty-boson" model, which considers bosons interacting in the presence of disorder [2]. This model predicts that for a field tuned transition with an arbitrary amount of disorder a true superconducting state exists at $T=0$, when vortices are localized into a vortex-glass phase and Cooper pairs are delocalized [3]. Above a critical field $H_C = H_{SI}$, vortices are delocalized and Cooper pairs localize into an insulating Bose-glass phase. A Bose-metal, with universal sheet resistance, should exist at the critical resistance [4]. Most "dirty-boson" analyses predict a continuous transition. A scaling analysis has been suggested [3] which seems to yield a good fit to experimental data in a limited range of temperatures and fields [6–8]. However, results of the type presented in this paper, as well as others [9–11], cast doubt on the generality of the theory. Other theories also predicted a pure SI transition, even in the presence of dissipation, and did not allow for a range of a metallic phase [18–20]. The possibility of a metallic phase intervening between the insulating and superconducting phases was first proposed by Mason and Kapitulnik [10], who suggested a new phase diagram for the SI system in which a superconductor-metal transition exists and depends on a new parameter, α , which describes a coupling to dissipation [10]. This idea can be connected to a theory by Shimshoni *et al.* [21] which explains low temperature metallic states in SI systems as an effect of dissipative quantum tunneling of vortices. In this model, the SI transition is percolation-like, with couplings between superconducting "puddles" in the superconducting phase and insulating "puddles" in the insulating phase. A different approach to obtaining a puddle-like structure was proposed by Spivak and Zhou [22]. In that paper it was argued that mesoscopic fluctuations of the order parameter at very low temperatures manifest themselves in multiple re-entrant transitions between superconducting and normal states; hence, the creation of puddles for which global superconductivity is obtained via an effective random SNS junctions array. Mason and Kapitulnik [10] also showed that at higher temperatures the system almost undergoes a superconductor-insulator transition with a correlation length exponent very close to that of classical percolation. This observation further strengthened the proposals [21,22] that the system breaks into puddles

that almost connect via a classical percolation process before settling into a new metallic phase that is dominated by vortex dissipation. The Josephson-Junction-like I-V characteristics are perhaps the most striking evidence that indeed the system breaks down into domains which are connected via Josephson tunneling. Further analysis of a puddle model consisting of strongly fluctuating superconducting grains embedded in a metallic matrix led Spivak *et al.* [25] to predict a metal-to-superconductor transition with a metallic phase just above the transition which is dominated by Andreev reflections from the almost superconducting grains. The resistance of such a phase has to be much lower than the "normal" resistance of the system, an occurrence that has consistently been observed in our samples. Another approach to a metallic phase in an SI system was recently taken by Dalidovich and Phillips [24] who showed that dissipation causes the metallic phase and ultimately is responsible for the insulating phase; in this case, a true superconducting state is expected as T vanishes.

In summary, we presented in this paper evidence of a genuine transition between a new metallic state and a superconducting state in 2D films. We believe that our experiment presents the first evidence for a $T=0$ quantum phase transition of this kind. While a simple phenomenology based on a "puddle" model of superconducting and metallic regions can qualitatively explain the main features of our experiment, more work is needed to fully understand the nature of the new metallic state and the superconducting transition.

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FIG. 1. Magnetoresistance of a 40\AA sample at 200 and 50 mK. Inset (marked on the main figure as a dashed box) shows the high field portion with the crossing point.

FIG. 2. Low field portion of the magnetoresistance shown in Fig.1. Dashed line represents a linear fit with an intersection field of 850 Oe. The inset shows the actual critical field of the sample of 185 Oe.

FIG. 3. Magnetoresistance near the critical field of the sample. Arrows show the direction of the field sweep. Curves are all shifted by 87 Oe to account for trapped flux in the 16T magnet.

FIG. 4. Dynamic resistance of a 30\AA sample at 200 Oe and 100 Oe.







